ON THE CONFINEMENT OF HIGH-TEMPERATURE PLASMA IN A TRAP WITH MAGNETIC MIRRORS

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Fig. 1

Figure 1: Fig. 1

Abstract

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L. V. DUBOVOI, V. P. FEDYAKOV

ON THE CONFINEMENT OF HIGH-TEMPERATURE PLASMA IN A TRAP WITH MAGNETIC MIRRORS

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In this work the confinement time of a plasma with hot electrons in a mirror-type trap was studied. To fill the trap with high-temperature particles, the method of turbulent plasma heating in a direct discharge was used (^{1}). The experiments were carried out in a quartz tube 1.2 m long and 12 cm in diameter, in deuterium at a gas pressure of $1—2 \cdot 10^{-5}$ mm Hg. Preliminary ionization of the gas was accomplished using the Penning-discharge mechanism. The transverse dimensions of the plasma column were limited by glass diaphragms with an internal aperture diameter $d = 8$ cm. The magnetic-field strength H_z in the region of the uniform part of the trap could be varied from 2 to 10 kOe at a constant mirror ratio of 1.5. The duration of the half-period of the field was 6 msec. The field uniformity in the region between the mirrors was no worse than 1%. The ultimate vacuum in the system was $2 \cdot 10^{-6}$ mm. The discharge electrodes were made of aluminum.

Fig. 1. Dependence of the confinement time of charged particles in the trap on the magnitude of the diamagnetic effect in the plasma. $H_0 \sim 4000$ Oe, $n \sim 2 \cdot 10^{12}$ cm^{-3}

The current I of the direct discharge intended for plasma heating was switched on at the moment of the maximum value of the magnetic field. In the experiments the discharge current could be varied from 1 to 45 kA; the duration of the current half-period was 5 μsec.

Determination of the mean energy stored in the plasma as a result of heating was carried out by measuring the magnetic flux $\delta\varphi = \pi d^2 \delta H_z / 4$ inside the plasma. The quantity $\delta\varphi$ was determined by integrating the e.m.f. induced in the turns of a winding encircling the quartz bulb. Measuring the magnitude of the current

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

I flowing through the plasma and the value of the quasistationary longitudinal magnetic field H_z outside the contour, and taking the plasma diameter to be equal to the internal diameter of the limiting diaphragms, from the equation of balance of magnetic and gas-kinetic pressures in the plasma it was possible at each given moment of time to determine the quantity $nk(T_e + T_i)$, or, taking into account that under the experimental conditions $T_e > T_i$ (^{1}), the quantity nkT_e.

The particle concentration in the plasma, needed to determine the electron temperature, was found by probing the plasma column with a microwave signal of wavelength 3 cm; from the measured quantities n and nkT_e, T_e was calculated. A rough check of the value of T_e for a strongly heated plasma was carried out by measuring the x-ray radiation emitted by the plasma.

The oscillograms in Fig. 2 show the behavior obtained in the experiments for the quantity δH_z, the change of the magnetic field in the plasma, for several values of the charging voltage on the capacitor V_0 feeding the discharge. Processing of the oscillograms shows that for values $V_0 \simeq$ 10–12 kV (Fig. 2a) the plasma is heated only weakly, and the absolute value of δH_z during the lifetime of the discharge current corresponds to the calculated value for the case of cold plasma with clearly expressed paramagnetic properties. The reversal of the sign of δH_z after the end of the direct-discharge current, corresponding to the expulsion of part of the magnetic flux from the plasma, indicates heating of the particles; and the amplitude and lifetime of the diamagnetic effect observed in this currentless plasma make it possible to determine the energy stored in it and the lifetime of the heated particles in the magnetic trap. It is also seen from the oscillograms that, as the discharge current increases, the quantity $\delta H_z \sim nT_e$ increases. Since the electron concentration measured by the microwave method changed little in the experiments, it may be unambiguously concluded that T_e increases strongly with increasing V_0. The effect has a clearly pronounced threshold character,

Fig. 2. Oscillograms of the magnetic field inside the plasma for values of the charging voltage on the capacitor feeding the current $V_0 = 12$ kV (a), 16 kV (b), 18 kV (c), and 20 kV (d). $C = 2.0$ μF. 1–δH_z, 2–dI/dt.

Fig. 3. Oscillograms of plasma transmission by a microwave signal with wavelength 3 cm (1), of the diamagnetic signal δH_z (2), and of the intensity of x-ray radiation (3) as functions of time. $H_z = 4000$ Oe, $\delta H_z/H_z \sim 0.03$, $n \sim 2 \cdot 10^{12}$ cm^{-3}. Time marks every 1 msec. The triggering time of the current I coincides with the jump in δH_z.

since electron heating is observed only for values of V_0 greater than 10 kV.

Characteristic of the curves shown are the short times during which the plasma-heating process takes place. Thus, for values $V_0 \gtrsim 20$ kV (Fig. 2c) the heating time is of the order of, or less than, 10^{-6} sec.

Figure 1 gives the experimentally determined dependence of the time for the diamagnetic signal to decrease by a factor of two, characterizing the confinement time of the plasma in the trap, on the quantity $\delta H_z/H_z \sim T_e$. It is seen that, with increasing T_e, the plasma confinement time τ increases monotonically and, for $\delta H_z/H_z \approx 0.03$ ($T_e \sim 10^4$ eV), reaches a value of the order of 1 msec.

Figure 3 shows time-aligned oscillograms of the passage of the 3-cm signal, the diamagnetic signal, and the X-ray emission from the plasma. It is seen that all three quantities change comparatively little during the lifetime of the magnetic field, indicating stable confinement of the heated plasma by the magnetic trap under the experimental conditions. The measured confinement time agrees satisfactorily with that calculated for the case of a plasma whose mechanism of escape from the trap is due to Coulomb collisions of the particles.

The maximum values obtained in the experiments, $\delta H_z/H_z \sim 0.04$, correspond to an average stored energy density in the plasma of the order of several units of 10^{16} eV$\cdot$cm^{-3}, which, for the measured value of the electron concentration in the plasma $n \simeq 2 \cdot 10^{12}$ cm^{-3}, corresponds to $T_e \simeq 10 \div 20$ keV. An independent estimate of the values of T_e, obtained from measurements of the X-ray emission, gives $T_e \sim 20 \div 30$ keV. Taking into account a number of factors that are difficult to allow for when determining T_e from the X-ray spectrum, one may consider that the values of the electron temperature obtained by the two methods are in satisfactory agreement. The experiments carried out point to the promise of further investigations of the turbulent method of plasma heating in a direct discharge with its subsequent capture in magnetic traps of various types.

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